

# An Alternative Evolutionary path to BMSPs

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## Abstract

We examine an alternative theoretical scenario for the formation of binary and millisecond pulsars via the accretion-induced collapse scenario of an O-Ne-Mg white dwarf. The new features of these evolutionary calculations are the inclusion of the effect of thermohaline mixing and also a self-consistent treatment of winds. The progenitor binary system consists of  $8 + 1.5 M_{\odot}$  stars in a binary orbit that allows the massive donor (primary) to fill its Roche lobe during an Early Case C mass transfer. The convective envelope of the primary ensures that the system evolves through a Common-Envelope phase. We follow in detail the evolution of the post-CE remnant of the primary up to the formation of an O-Ne-Mg white dwarf. The subsequent evolution of the secondary, whose both mass and chemical abundances have been modified by thermohaline-mixing, passes through an LMXB phase and ends up as a binary and millisecond pulsar. This proposed scenario can be applied to a number of observed systems of BMSPs.

## Introduction

Binary millisecond pulsars (BMSPs) form a distinct class of degenerate binaries characterised by rotational periods less than 30 ms and relatively weak dipole surface magnetic field strength ( $B_s < 10^{10}$  G). They are believed to be descendants of LMXBs (Bhattacharya and van den Heuvel 1991). The following evolutionary scenarios have been proposed to explain the observed characteristics of BMSPs according to a recent review by Taam (2000) a) by Case A evolution from binaries with a low-mass donor and short orbital period ( $< 1$ -2 days); this leads to the formation of BMSPs with a He WD companion of mass  $< 0.2 M_{\odot}$  and orbital period  $< 1$  d. b) by Case B evolution of binaries with an intermediate mass donor ( $2.25 < M < 6 M_{\odot}$ ); this leads to the formation of CO WD companions of mass  $> 0.35 M_{\odot}$  and orbital periods  $< 20$  d; c) through common-envelope (CE) evolution. Here short-period ( $P_{\text{orb}} < 1$  d) BMSPs can be formed from:  $c_1$ ) unstable low-mass Case B mass transfer, which yields helium WDs in the mass range  $0.2$ - $0.5 M_{\odot}$ , and  $c_2$ ) unstable Case C evolution, which yields CO white dwarfs of mass  $> 0.6 M_{\odot}$ . Wide BMSPs are produced by either stable low-mass Case B or stable low-mass Case C mass transfer from donors  $< 1.4 M_{\odot}$ , in systems with initial orbital periods greater than a few days producing He- or CO WDs, respectively. The so far proposed models and theoretical calculations assume that the donor of the LMXB system is of solar chemical composition. We call this classical case. In the following sections we will explore the case of non-solar type donors and apply the new findings to some observed binary and millisecond radio pulsars (BMSPs).

## The alternative model

The alternative scenario for the explanation of the observed characteristics of BMSPs is based on the formation of non-solar type donors in the progenitor LMXB system. The idea is based on the inclusion of the effect of thermohaline mixing in the radiative layers of the donor before the formation of an LMXB, as a result of an interaction (through mass transfer) between the two members of the primordial binary. A detailed description of the new proposed model is given as follows: The NS is modelled to be produced by the accretion of mass onto an O-Ne-Mg WD. The white dwarf was the evolutionary product of a binary with a massive primary and a less massive component that evolved through a Case C mass transfer and a Common-Envelope phase. More specifically, the initial binary consists of  $8 M_{\odot}$  star and a low-mass companion of  $1.5 M_{\odot}$  in a wide orbit. Once the  $8 M_{\odot}$  star in this system overflowed its Roche lobe at point  $A_1$  in Fig. 1, a common-envelope starts forming (phase a), in which the  $1.5 M_{\odot}$  companion spiralled in (point  $A_1$  in

Fig. 1). At  $A_2$  there was the first underflow of Roche lobe overflow. However, this moment does not mark the termination of CE phase, since due to thermal pulses the star again overfills its Roche lobe. The Common Envelope was ejected in this process, at point  $A_3$ , leaving a system consisting of a helium shell burning remnant of the primary (with a very thin H-rich envelope) plus the initial secondary (phase b). This thin hydrogen envelope is soon removed from the post-CE primary's remnant due to winds at point  $A_4$ . During the late stages of helium shell burning of the primary's remnant, points  $A_5$ - $A_6$ , the helium-envelope of this star expands and some  $0.7 M_\odot$  of helium is transferred to the  $1.5 M_\odot$  secondary, whose mass grows to  $2.2 M_\odot$ , after accretion and mixing due to thermoohline-mixing (phase c). The remnant of the primary cools as an  $1.1 M_\odot$  O-Ne-Mg WD at point  $A_8$  (phase d). (At point  $A_7$  the WD has reached its highest effective temperature). Phase (c) is responsible for the possible formation of non-solar donors in the subsequent LMXB system. The timescale for phases from (a) through (g) is also shown in Fig. 1. We then study the evolution of the secondary star, in a binary system consisting of a  $2.2 M_\odot$  secondary and an  $1.1 M_\odot$  O-Ne-Mg white dwarf at a starting value of the orbital period of  $P_{\text{orb},0} = 0.8$  d (Case A of evolution. When the  $2.2 M_\odot$  helium-enriched companion of this WD begins to overflow its Roche lobe the relatively high mass transfer rate ( $\dot{M}$ ) that ensues ( $> 10^{-7} M_\odot \text{yr}^{-1}$ ) turns the WD into a supersoft X-ray source, with stable nuclear burning on the surface of the WD (phase e). As a result of the nuclear burning of H and He on to the WD surface, the WD can grow in mass up to the Chandrasekhar limit which presumably triggers its collapses to form a NS. We take into account the effect of the SN explosion on the binary orbit and follow the evolution of the system with a newborn NS (phase f). The post supernova binary orbit widens as a result of the neutrino emission corresponding to mass loss of about  $0.14 M_\odot$ . The system now consists of an NS ( $1.26 M_\odot$ ) and a Main-Sequence Companion of  $1.37 M_\odot$  of non solar composition which can be observed as an LMXB when the donor overfills its Roche lobe (phase g) shown in Fig. 1. The accretion of mass on to the NS surface is assumed to cause its dipole surface magnetic field strength to decay and reach a low value of about  $2 \times 10^8$  G. During its LMXB phase, the pulsar is recycled to the ms range. At the termination of the Roche lobe overflow phase a pulsar is switched on. The produced relativistic pulsar wind induces an evaporative wind from the secondary that may change the evolution of the binary system as is observed for the binary radio pulsar PSR 1718-19 (Taylor et al. 1993). We formally include the effect of the pulsar relativistic wind and the screening effect for the calculation of the evolution of the donor. We assume a change in the boundary conditions due to X+ $\gamma$ -ray heating after Tout (1989) and the pulsar radiation and screening effect of the donor are also modelled according to Muslimov and Sarna (1993).

## Results and Description of the Figures

Figure 1 describes the evolution in the H-R diagram of a system with initial component masses  $8 + 1.5 M_\odot$  and initial orbital period (at ZAMS) of 500 d. After a second Roche lobe overflow during He-shell burning of the post-CE remnant, the secondary mass increases up to about  $2.2 M_\odot$ . Symbols here, defined in the left-hand side of the figures, represent time intervals on the evolutionary tracks. Note the non-solar chemical composition of the secondary star due to the effect of thermohaline-mixing. Figure 2 represents the alternative evolution in the  $P_{\text{orb}} - M_s$  diagram of the post-CE binary with a He-enriched secondary of  $2.2 M_\odot$  and an  $1.07 M_\odot$  O-Ne-Mg white dwarf. The starting orbital period is  $\sim 0.8$  d.  $P_{\text{orb}}$  changes are shown with thick solid lines, while  $M_{\text{WD}}$  is shown with thick dashed lines. For comparison reasons, thin lines show the evolution of  $P_{\text{orb}}$  and  $M_{\text{WD}}$ , respectively, for a secondary of the same mass  $2.2 M_\odot$  but of solar composition. Here the O-Ne-Mg WD does not grow sufficiently to collapse to a NS. Figure 3 gives the alternative evolution in the  $\dot{M} - M_{\text{WD}}$  diagram with thick solid and dashed line, respectively.

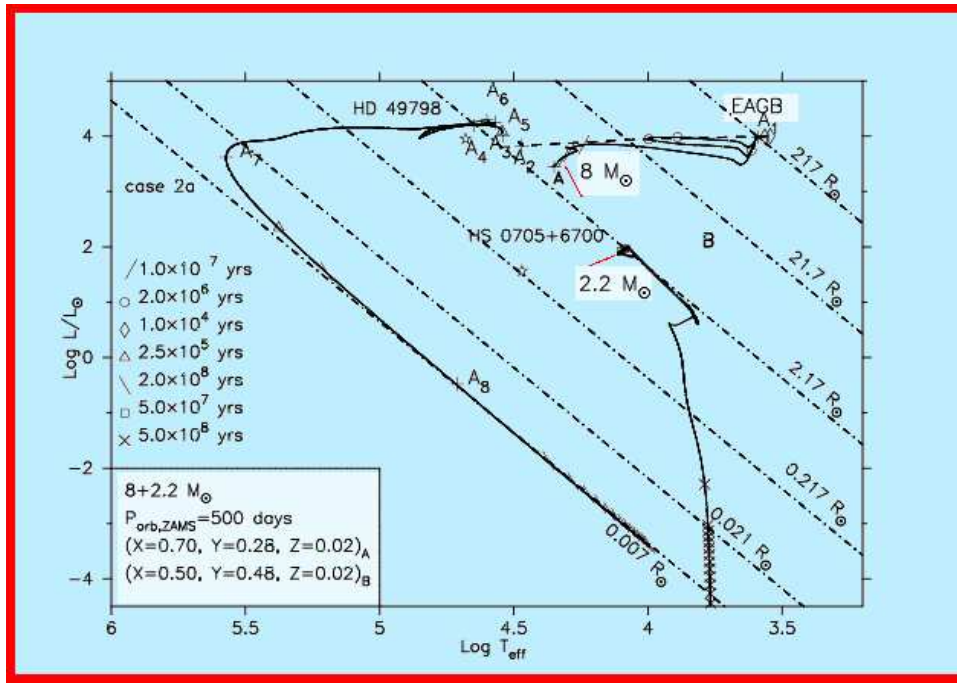


Figure 1: Evolution in the H-R diagram of a system with initial component masses  $8 + 1.5 M_{\odot}$  and initial orbital period (at ZAMS) of 500 d. The alternative evolution (labelled as Case 2a) has two phases of Roche lobe overflow. This evolution pathway includes two phase of mass transfer, the first being at the AGB (Case C evolution) and the second being when the helium star again overfills its Roche lobe while burning helium at shell. After the second Roche overflow lobe, the secondary mass has reached  $2.2 M_{\odot}$ . Symbols here, defined in the left-hand side of the figures, represent time intervals on the evolutionary tracks. The crosses correspond to the evolutionary phases  $A_1$  through  $A_8$  as described in the text. Note the non-solar chemical composition of the secondary star due to the effect of thermohaline-mixing.

The system may form an LMXB system via the AIC (accretion-induced collapse) scenario of the O-Ne-Mg white dwarf when its mass reaches the Chandrasekhar limit. For comparison reasons, thin lines show the evolution of  $\dot{M}$  (full lines) for a secondary of the same mass  $2.2 M_{\odot}$  but of solar composition. Here the O-Ne-Mg WD does not grow sufficiently to collapse to a NS. The nearly horizontal dotted lines define the region of steady H burning, thick lines for the alternative evolution and thin lines for the classical case of donors of solar composition. Similar results have also been obtained and for  $P_{\text{orb},0} = 1.4$  d (Bitzaraki et al. 2003). The change of the orbital period versus the mass of the secondary,  $M_2$ , for the produced LMXB system is shown in Fig. 4. The initial increasing slope of the curve is due to unstable mass transfer mode (super-Eddington mass transfer rates) from the more massive to the less massive component (NS). The effect of the Angular Momentum Loss (AML) on the binary orbit is then compensated by the isotropic re-emission of the accreted matter from the inner region of the accretion disk, (Bhattacharyya and van den Heuvel 1991) a part of the accreted matter corresponding to  $\dot{M} - \dot{M}_{\text{edd}}$  is assumed to be carried away with the specific angular momentum of the NS. Following this stage, the mass transfer occurs at sub-Eddington rates. Then, AML due to the magnetic braking results in a shrinkage of the binary orbit. The subsequent increase of the orbital period is due to the gradual development of degeneracy in the core of the secondary which ends up as a low-mass He white dwarf.

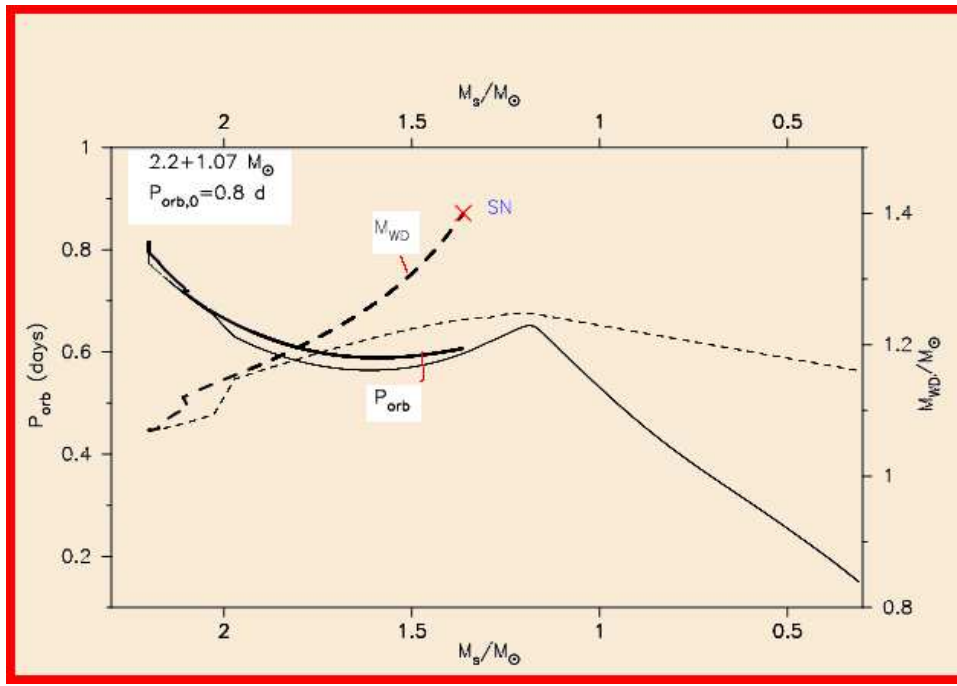


Figure 2: Diagrams of  $P_{\text{orb}}$  and the white dwarf mass as a function of the secondary mass,  $M_s$ , for the post-CE binary with a He-enriched donor of  $2.2 M_{\odot}$  and an  $1.07 M_{\odot}$  O-Ne-Mg white dwarf is shown with thicker solid lines. The starting orbital period is  $\sim 0.8$  d. The white dwarf mass as a function of  $M_s$  is shown with thicker dashed lines for the alternative evolution. For comparison, thin lines show the evolution for a donor (of the SSS) of the same mass and initial orbital period, but of solar chemical composition.

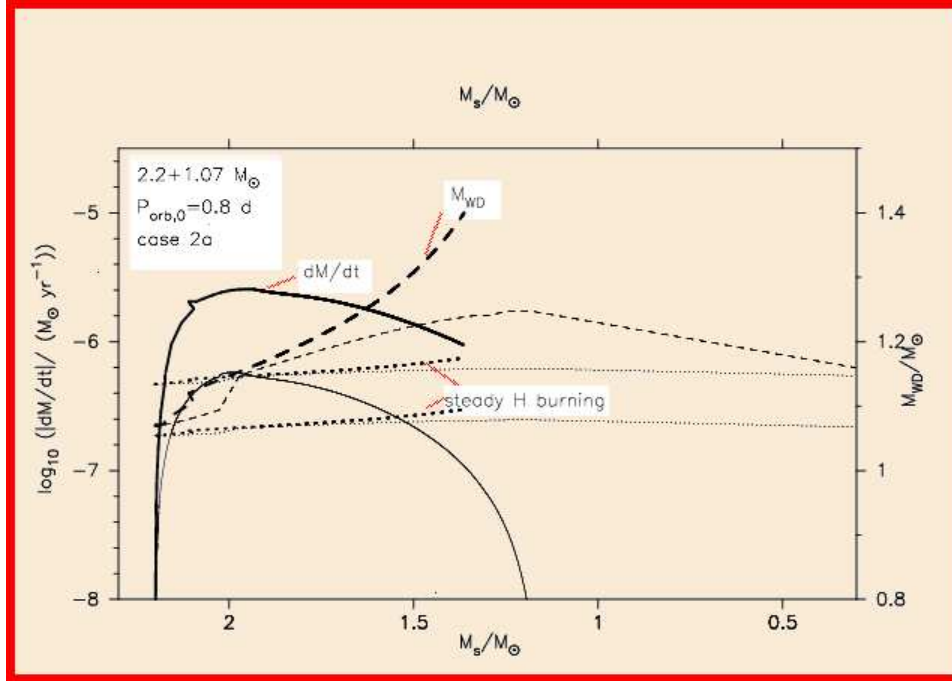


Figure 3: Evolution of  $\dot{M}$  and  $M_{\text{WD}}$  versus secondary mass (thick full and dashed line, respectively), for the alternative evolution. The system may finally form an LMXB system via the AIC (accretion-induced collapse) scenario of the O-Ne-Mg white dwarf when its mass reaches the Chandrasekhar limit. For comparison reasons, thin lines show the evolution for a donor (of the SSS) of the same mass  $2.2 M_{\odot}$  but of solar composition. Here the WD does not grow sufficiently to produce an NS. The nearly horizontal dotted lines define the region of steady H burning, thick lines for the alternative evolution and thin lines for the classical case of donors of solar composition.

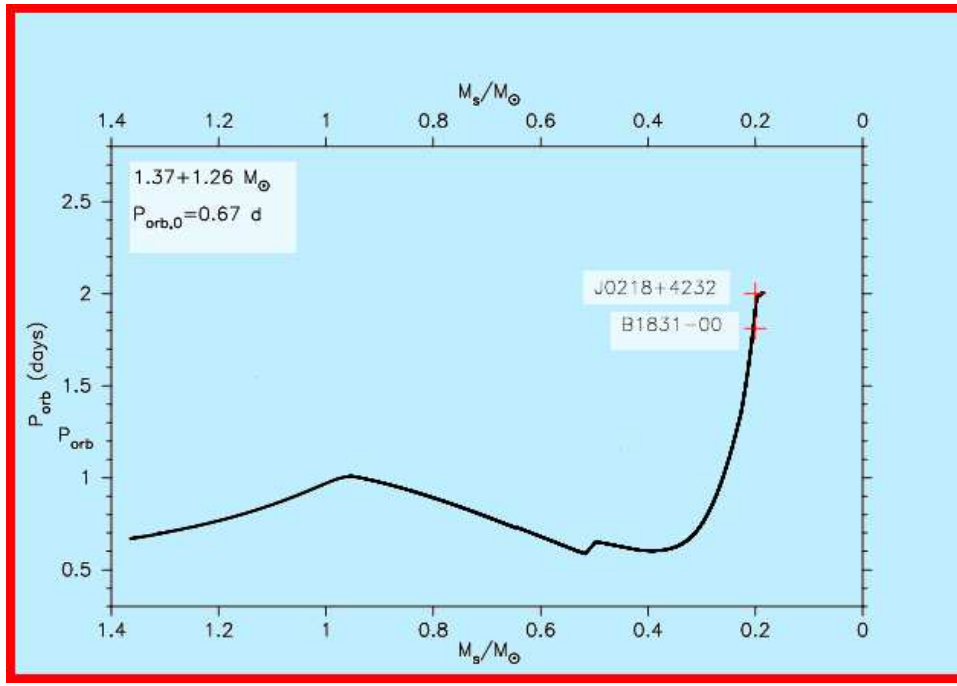


Figure 4:  $P_{\text{orb}} - M_s$  diagram of the produced LMXB system. The starting orbital period (post-supernova orbit) was assumed to be about 0.67 d. The initial binary masses are a NS of gravitational mass of  $1.26 M_{\odot}$  and the initial secondary (the donor of the LMXB) of mass about  $1.37 M_{\odot}$ .

## Confirmation by observations - Examples

### PSR J0218+4232

PSR J0218+4232 is a millisecond pulsar with rotation period (pulse period) of 2.3 ms and orbital period of 2 days. The companion is a low-mass white dwarf (probably a He white dwarf) as has been reported by Navarro (1995). The recently reported high-resolution spatial and timing observations of PSR J0218+4232 obtained with Chandra mission give the pulse period,  $P_{\text{spin}} = 2.35$  ms, orbital period 2.0288 days and  $\alpha \sin i = 1.9844$  lt-s (Kuiper et al. 2002). Stairs et al. (1999) have measured the magnetic inclination angle from radio polarization profiles and found that the magnetic inclination angle relative to the rotation axis is about  $0^\circ$  ( $\approx 8^\circ \pm 11^\circ$ ). We use the latter value to calculate the relativistic pulsar wind and the evaporative stage of the donor star. The proposed alternative evolutionary model can easily explain the observed characteristics of PSR J0218+4232.

### PSR B1831-00

PSR B1831-00 has been suggested to have formed via the AIC scenario due to its high magnetic field strength in comparison to other binary and millisecond radio pulsars (van den Heuvel and Bitzaraki, 1995). We have tested the above evolutionary scenario to explain properties of this interesting pulsar. Should, during the LMXB phase, all mass be accreted to the NS then a gravitational mass of about  $0.2 M_{\odot}$  would be expected to have accreted on the NS surface. This amount is sufficient to decrease the magnetic field strength to an average value of  $2 \times 10^8$  G. The value  $B_s = 8.7 \times 10^{10}$  G of PSR B1831-00 shows that it can not have accreted this amount of mass. Recently, Sutantyo et al. (2000) discuss evolutionary scenarios for the formation of PSR B1831-00 in terms of the "standard" scenario and the AIC model. Their "AIC" model, however, does not include mass loss from the system during the supernova explosion which forms the NS. Also, no mass loss

due to the centrifugal propeller effect is included. They conclude that either model can not explain satisfactorily the observed high surface magnetic dipole strength. As a result, they propose that the existence of this system may be indicative of its formation through a CE phase (Tauris et al. 2000), but again, they confront to a major problem: the small white dwarf mass. The proposed AIC model for the formation of PSR B1831-00 can reproduce well observational data such as the mass of the white dwarf and the binary orbital period as seen in Fig. 4. If the NS can accrete up to  $0.2 M_{\odot}$  in the absence of the propeller effect, then its magnetic field strength would not have acquired the high value  $B_s = 8.7 \times 10^{10}$  G. This implies that this system must have undergone severe mass loss e.g during the supernova event of the WD collapse to form a NS. Since, this would require much more extensive calculations we postpone this task for a future work.

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